Author response to the reviewers comment from Timothy Hill on the manuscript amt-2018-392: “Low-cost eddy covariance: a case study of evapotranspiration over agroforestry in Germany”

We thank you for your feedback, suggestions and helpful comments on the manuscript. In the current document we give a point-by-point answer on above mentioned referee report. We show first the referee comments (**RC**) and secondly the answer of the authors (**AR**). Changes made in the manuscript can be found in the track changes document attached to the current document. Figure numbers and references refer to the track-changes document, if not otherwise stated. We are still editing the manuscript and will perform minor changes explicitly stated in the text.

1. RC: *This manuscript provides an interesting approach to low cost ET measurements that have been tested at large number of sites and is a useful addition to the literature. The instrumental approaches described are shown to be effective in comparisons with the LI-7200 systems. The comparison of cumulative ET (Figure 11) is impressive – it would be informative to show cumulative ET lines (perhaps in appendix) to illustrate if the seasonal responses are comparable. Furthermore it would be worth a look in the literature to put in context the size of the differences (are they close to the disagreement between conventional systems).*

1. AR: Figure 12 shows the cumulative sum of half-hourly evapotranspiration rates for the respective campaign times of approximately four weeks duration. The data were filtered for implausible values and gaps were not filled for this analysis to reduce the inferred error caused by gap-filling. We included the cumulative sums for the respective campaign periods in Figure 13. The figure points out that both set-ups recover properly the temporal changes of evapotranspiration during the campaign periods, caused by the plant physiological response of the underlying ecosystem to changes in meteorological driver such as incident radiation, air temperature and the vapour pressure deficit. The differences between both set-ups at the Dornburg AF site is caused by a period of bad performance of the low-cost system. If the period is discarded from the data, the difference between EC and EC-LC at the Dornburg AF site is comparable to differences at the other sites, as shown in Figure 1 of the current document. We will change and discuss the figure accordingly in the manuscript.

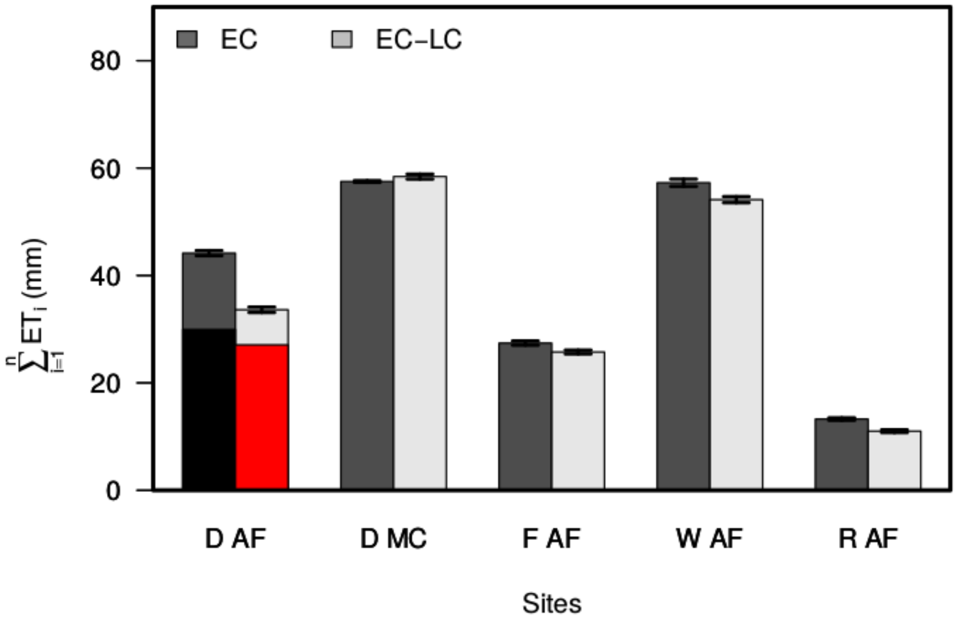

Figure 1: Cumulative evapotranspiration rates for the EC and EC-LC set-ups for Dornburg agroforestry, (D AF), Dornburg monoculture, (D MC), Forst agroforestry, (F AF), Wendhausen agroforestry, (W AF), and Reiffenhausen agroforestry, (R AF) over the respective campaign periods (Table \ref{tab:CampaignTime}). The error bars correspond to the summed random uncertainties, which were added to the cumulative evapotranspiration rates. Incomplete records with either of EC or EC-LC missing were omitted. The black and the red bars indicate the cumulative sum of ET with data discarded.

A comparison of cumulative sums for both set-ups and hence a description of their seasonal response over the course of a whole year is not possible because the measurement campaigns were only of four weeks duration. We included some results from some studies on the comparison of separate gas analyser set-ups sharing the same sonic anemometer. The differences between systems found therein are comparable to differences we found for our low-cost set-up.

2. RC: *My first main comment is that I would please like to see are details on: 1) the cost (since this is a low cost system, how low cost is it?); 2) power usage; 3) construction (details needed for people to replicate the build), and 4) maintenance of the low cost system. I see these details as extremely valuable for any readers to replicate this study.*

2. AR: We included more required information in the section “Instrumental set-up - Low-cost eddy-covariance (EC-LC) installation”.

Changes in the manuscript:

2.2.3 Low-cost eddy-covariance (EC-LC) installation

The low-cost eddy-covariance set-up ~~comprised of~~ shared the same ultrasonic anemometer (uSONIC3-omni) as used for the conventional EC ~~method and a~~ set-up. The water vapour mole fraction was derived from the combined digital pressure, relative humidity and air temperature sensor ~~(~~BME280 ~~,~~ manufactured by *Robert Bosch GmbH*, Stuttgart, Germany ~~)~~ (hereafter named thermohygrometer, Fig. 2 depicts the low-cost set-up). The measuring principle is resistive, capacitive and based on diode voltage measurements for the air pressure, humidity and temperature sensor, respectively. The ultrasonic anemometer measured the three-dimensional wind speed and the ultrasonic temperature at a frequency of 20 Hz, whereas the thermohygrometer measured the air temperature, relative humidity and air pressure at a sampling frequency of 8 Hz. The specified response time of the thermohygrometer for relative humidity measurements is 1 s to overcome 63 % of a step change from 90 % to 0 % or 0 % to 90 % relative humidity ~~.~~ at 25 °C air temperature.

The thermohygrometer was placed 0.5 m below the centre of the sonic anemometer in a PVC housing to protect the thermohygrometer from precipitation. ~~A~~ The PVC housing consisted of an outer and an inner cylinder. The inner cylinder was perforated on the top to provide a continuous air flow of 15 lpm, generated by a ventilator (HA30101V3-0000-A99, *Sunonwealth Electric Machine Industry Co. Ltd.*, Fresnes Cedex, France). The ventilator was placed below the thermohygrometer ~~provided a continuous air flow of 15lpm.~~ inside the inner cylinder. The volume of the inner cylinder was 98.1 cm^3.

The absolute accuracy tolerance of the ~~thermohygrometer~~ relative humidity sensor was specified as ± 3 % ~~relative humidity (Bosch Sensortec GmbH, 2016). Data~~ for 20 to 80% relative humidity at 25 °C, for the temperature sensor an absolute accuracy tolerance of ± 0.5 °C at 25 °C and ± 1 °C for a temperature range of 0 to 65 °C was specified and for the pressure sensor an absolute accuracy tolerance of ± 1 hPa (300-1100 hPa, 0-65 °C) (Bosch Sensortec GmbH, 2016).

Digital data from the thermohygrometer were recorded via the i2c protocol and stored on a RaspberryPi model B+ (*Raspberry Pi Foundation*, Cambridge, UK). The potential of the low-cost EC set-up are replicated measurements of evapotranspiration across different ecosystems. The relative cost of the low-cost set-up (featuring a sonic anemometer, a RaspberryPi and the thermohygrometer of low cost) is about 8-10 % of a conventional EC set-up.

The thermohygrometer points out with very low power consumption of approximately 3.6 μA at a sampling frequency of 1 Hz (9.4e-5 W at 8 Hz, powered with 3.3 V and if all three variables are measured simultaneously) and the RaspberryPi has a maximum power consumption of about 1.1 W if all three variables are measured at the same time. The set-up requires low maintenance. The sensors needs to be properly installed, such as they are protected against precipitation. Furthermore, a stable power supply is required. Currently, two out of ten sensors were deployed for a duration of two years.

3. RC: *The second main comment I have is that it would be very informative to see details about the actual frequency response of the low cost sensors (RH and T) and if there are environmental dependencies on these response times. It would be good to see a comparison of the sensor specification and actual response times derived from the spectral analyses. A related point is, what was the size of the frequency response correction?*

3. AR: We estimated the sensor time constant of the temperature and relative humidity sensor of the BME280 in a lab experiment. The time constant of the temperature sensor was 23.3 ± 0.9 s as a mean over 4 replications. Preliminary results showed a faster time response of the relative humidity sensor. The lab experiment will be continued in the next days and results will be included in the revised manuscript, perhaps in the Materials and Methods section.

In the following we want to address the spectral response characteristics of the BME280 thermohygrometer for water vapour measurements in two ways, first, as the cut-off frequency and the derived sensor time constant and, second, as the spectral correction factor for water vapour.

Cut-off frequency and sensor time constant

We estimated a theoretical cut-off frequency according to the given time constant, τ_c , with the following equation:

$$f_c = \frac{1}{2\pi\tau_c} \quad (1)$$

The nominal response time of the relative humidity sensor is one second for a step change in relative humidity from 0 to 90 and 90 to 0% relative humidity at 25°C ambient air temperature, as stated in the specifications. A theoretical cut-off frequency of 0.16 Hz (6.3 s) results from equation 1 of the current document.

In comparison to the theoretical cut-off frequency, we estimated a cut-off frequency from spectra of the the water vapour mole fraction. We estimated the cut-off frequency as the frequency of the intercept between the maximum water vapour spectral energy and the linear fit of the energy spectrum in the inertial sub-range (between ~ 0.1 and 1 Hz) on a double logarithmic scale. The signal below the cut-off frequency is attenuated.

Under field conditions the mean cut-off frequency was 0.063 ± 0.02 Hz for the low-cost set-up and 0.3 ± 0.2 Hz for the EC set-up across five plots and all humidity classes (30-90% relative humidity). The mean time constant calculated from the cut-off frequency was 2.802 ± 1 s for the EC-LC set-up and 0.648 ± 0.3 s for the EC set-up, respectively.

We found an exponential increase of the time constant with increasing relative humidity for both the EC and the EC-LC set-ups (see Figure 2 of the current document). We are not able to reproduce the response time of 1 s even under very dry ambient conditions. The main cause are different ambient conditions than given in the specifications. The estimated time constants consider a relative humidity dependency, but not a temperature dependency. For a temperature of 25 ± 1 °C the time constant for the water vapour spectra was equal to the time constant at 30% relative humidity.

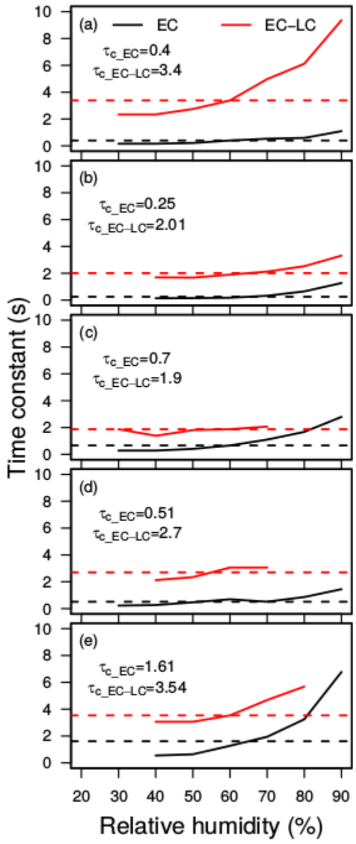

Figure 2: Time constant against relative humidity (from 20 to 90% in 10% classes) for the EC (black solid lines) and the EC-LC (red solid lines) set-up. Dashed lines and the values written correspond to the median time constant for the respective set-ups. Sites correspond to Dornburg AF, (a), Dornburg MC, (b), Forst AF, (c), Reiffenhausen AF, (d), and Wendhausen AF, (e).

Spectral correction factor for water vapour

Site	**Spectral correction factor (-)**		**Spectral correction factor flux magnitude change (%)**	
Method	**EC**	**EC-LC**	**EC**	**EC-LC**
Dornburg AF	1.12	1.78	6.9	40.82
Dornburg MC	1.21	3.05	14.3	60.9
Forst AF	1.1	1.99	9.9	47.7
Reiffenhausen AF	1.11	1.31	9.4	42.3
Wendhausen AF	1.19	1.74	5.9	21.83
Mean+-sd	**1.146** ±0.05	**1.974** ±0.65	**9.28** ±3.3	**42.7** ±14.1

Table 1: Median spectral correction factor and the impact of the spectral correction factor on the flux magnitude change.

We found a higher frequency correction factor for water fluxes (combines the correction for high and low-frequency losses) obtained by the EC-LC set-up than for the EC set-up with a median flux increase of 97.4% and 14.6% (see Table 1 and Figure 3 of the current document), respectively.

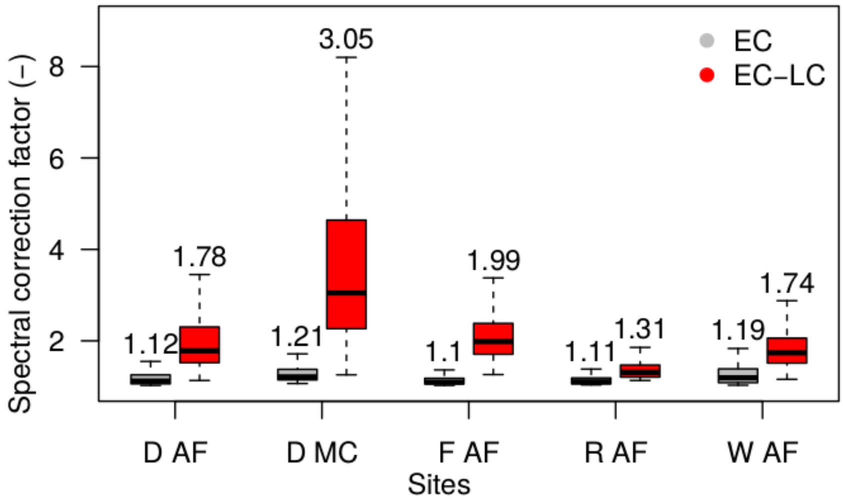

Figure 3: Box-whisker plot of spectral correction factors for the EC (grey) and the EC-LC (red) set-up for all sites, e.g. Dornburg AF, "D AF", Dornburg MC, "D MC", Forst AF, "F AF", Reiffenhausen AF, "R AF" and Wendhausen AF, "W AF". Values indicate the median spectral correction factor. Error bar

The effect of the spectral corrections on a flux magnitude increase was most pronounced for the low-cost set-up than for the conventional EC set-up with an overall flux magnitude increase of 42.7 ± 14.1 % and 9.28 ± 3.3 % for the EC-LC and the EC set-up, respectively (see Figure 4 and Table 1 of the current document).

We found the highest median spectral correction factor (3.05) and the highest flux magnitude increase (60.9%) caused by the high-frequency correction for the low-cost set-up of the monocultural agriculture plot of Dornburg. We interpret the higher spectral correction factor as caused by different measurement heights, with a measurement height of 3.5 m at the monocultural agriculture plot of Dornburg and a measurement height of 10 m at the agroforestry plot of Dornburg. At the lower tower high frequency eddies are more likely than at the taller tower. As the nominal time response (1 s) given in the specifications and the estimated time response are quite low, the flux loss is quite high and needs to be corrected for. We will include the information presented in the current document also in the revised manuscript.

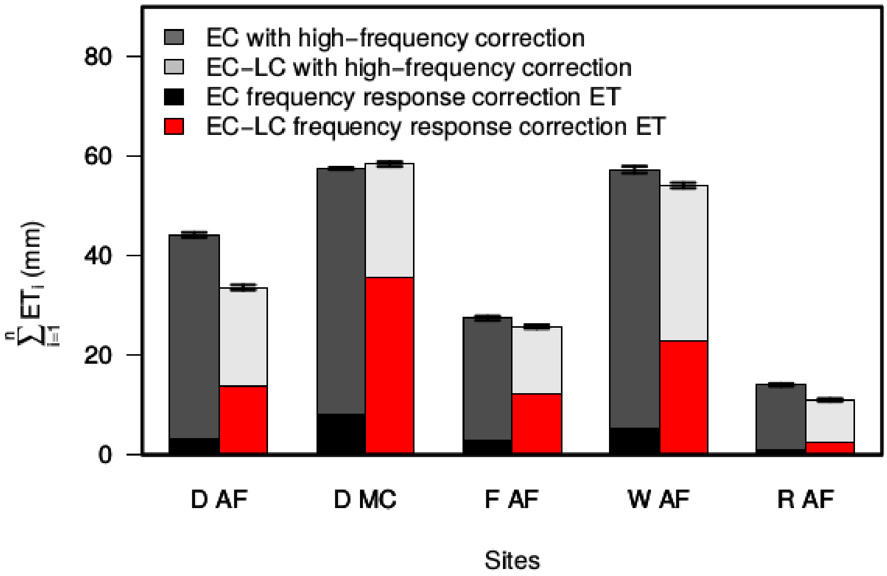

Figure 4: Barplot of cumulative sums of ET for the EC and the EC-LC set-up for all sites. Only data available at each time step and for both methods were used. The black and red bars indicate the summed ET corresponding to the frequency corrections. The error bars correspond to the summed random uncertainties, which were added to the cumulative evapotranspiration rates. Incomplete records with either of EC or EC-LC missing were omitted.

4. RC: *My third main query is what did the energy balance closures look like? ALthough an incomplete assessment of the ET, it would be informative to know the closure for the systems and sites.*

4. AR: We estimated the energy balance closure (EBC) of both systems at all sites. For the sites shown in the current manuscript we found EBCs similar to agricultural fields with a maximum of 88% and a minimum of 76% for the conventional EC set-up. The EBC of the low-cost set-up was lower relative to the conventional EC set-up at the agroforestry plots, according to an observed underestimation of the latent heat fluxes at those sites. Whereas, at the monoculture sites the EBC was higher for the low-cost set-up compared to the conventional EC set-up according to overestimated latent heat fluxes relative to conventional EC. Further analysis on the EBC is part of a separate study, currently in internal review.

5. RC: *Abstract: - A (pedantic) comment on the assumption that Eddy Covariance is appropriate for homogeneous land surfaces: Whilst arguably true (depending on the errors associate with EC) the assumption of homogeneity first needs to be tested using a suitable experimental design. See Hurlbert 1984 (Pseudoreplication and the Design of Ecological Field Experiments). Otherwise our implicit assumption is that the (non-flux) data we have about the full extent of the terrain (which might be limited to little more than a visual/reflectance based observations) is sufficient to predict the fluxes (or at least the variability - or lack of - in fluxes) – and if this is the case why use EC?*

5. AR: The homogeneity of the underlying surface is an assumption of the EC method. Sure, it is not possible to predict a flux from a visual based observation, but we can assess the homogeneity of the landscape/ecosystem purely visual. This includes the assumption that if the ecosystem seems homogeneous without major disturbances, the measured flux is also homogeneous at each point of the ecosystem. We therefore assume that the plant physiological response to biophysical drivers is the same for the ecosystem of interest.

Related to this discussion, the manuscript focus on an instrument comparison. We assume that the measured flux originating from the same ecosystem is the same for both set-ups (installed on the same tower) and therefore the impact of the ecosystem heterogeneity on fluxes is also the same.

6. RC: *-Line 8: Given the general lack of energy balance closure for the EC method, I don't think the 'true' ET flux is known. Therefore, 'underestimation' and 'overestimation' are more accurately termed 'underestimation relative to the conventional system'.*

6. AR: It was not entirely clear which line you refer to. Nevertheless, we interpreted your comment as a general one and checked the formulations throughout the whole document and changed them accordingly.

7. RC: *Page 3: Can you describe the site fetch? What are the heights of the trees and the crops? Reiffenhausen is a small site 18,700 m2 (~1.9 ha), what is beyond the extent of this site (and likely in your flux footprint)?*

7. AR: We included a purely descriptive explanation on the site fetch in Section "Site description" for the respective sites, because an extensive discussion of the flux footprint is not the scope of the current manuscript. A description and visual presentation of the flux footprint will rather be part of a manuscript currently in internal review.
Mean tree heights were included in "Table A1. Site locations, agroforestry geometry and stand characteristics" for the respective years the campaigns took place. Tree heights include the standard deviation and the number of trees included in the calculation.
Nevertheless, we think that the flux footprint information for the current manuscript is only of minor importance because it is mend to be a technical paper. Additionally, we argue that the two set-ups should effectively sample the same air and therefore the flux footprint should be the same for both set-ups. But we are aware that a comparison of different land use systems regarding the exchange of trace gasses between the ecosystem and the atmosphere require a proper evaluation of the flux footprint.

Changes in the manuscript on the flux footprint:

According to a flux footprint climatology (valid for the respective campaign and only daytime data according to a global radiation $R_G > 20\,W\,m^{-2}$ were used) analyses performed with the Flux Footprint Prediction online tool developed by Kljun et al. (2015), we found a 90 % flux magnitude contribution of the agroforestry plot of Forst and the monoculture plot of Dornburg and a 80 % flux magnitude contribution of the agroforestry plots of Dornburg and Wendhausen. The smallest agroforestry system of Reiffenhausen contributed the least to the measured turbulent flux with 60 %. Outside the agroforestry plot, fluxes were affected by nearby crop fields and forests in about 400 m distance to the flux tower in northerly direction and about 200 m distance in southerly direction, respectively.

Changes in the manuscript regarding the tree height:

Table A1. Site locations~~and~~, agroforestry geometry and stand characteristics.

Site	Coordinates	No. of tree alleys	System size [m^2]	Relative tree cover	Tree height [m]
Reiffenhausen	51°24'N 9°59'E	3	18700	72%	4.73±0.32 (n=69, BHD≥1 cm)
Mariensee	52°34'N 9°28'E	3	69260	6%	4.01±0.33 (n=96)
Wendhausen	52°20'N 10°38'E	6	179738	11.52%	6.21±0.4 (n=114)
Forst	51°47'N 14°38'E	7	391300	12%	6.5±1.8 (n=161)
Dornburg	51°47'N 11°39'E	7	508723	8%	6.4±0.64 (n=160)

8. RC: *Discussion: - I am reluctant to recommend citing my own paper, but as it is one of the only other studies to calculate ET from a low cost RH sensor, I think comparisons with the LE fluxes/approach from Hill GCB 2017 (and any others) should be made somewhere in the discussion.*

8. AR: Indeed, we apologize this and considered your study in the discussion of differences between the two different set-ups along with other studies not particularly focussing on low-cost sensors, but on the comparison of different conventional eddy covariance set-ups.

9. RC: *-Page 6 It would be useful to know the indicative cost and power usage for both systems. What is the volume of the thermohygrometer housing? What is the form of the housing? What response time (and measurement principle) did the temperature sensor of the BME280 use?*

9. AR: We included more information on the set-ups design in the revised manuscript and gave more information in AR 2 of the current document.
The response time of neither the temperature sensor nor the pressure sensor was explicitly stated in the sensor specifications. See more information on the response time in the author response 3 of the current document. The measurement principle of the temperature sensor is based on diode voltage measurements (personal communications with the manufacturer; according to the manufacturer specific details are confidential). We included more information on the measurement principle in the manuscript, please see AR 2.

10. RC: *- Page 6: it is not entirely clear to me if the systems shared the same sonic, and if not, what was the spatial separation of the comparison system?*

10. AR: Yes, the two set-ups shared the same sonic anemometer and we clarified this in the manuscript. Please see AR 2.

11. RC: *-Page 7: I am interested in how much data was filtered through QC and how you filtered data for the LC system?*

11. AR: The raw data, such as the air temperature, the relative humidity, air pressure, the 3D wind components and the sonic temperature, were filtered for upper and lower limits. The overall amount of data discarded by upper and lower limits was not significant.

Latent heat fluxes were filtered for implausible values with lower and upper limits of -50 and 500 W m^{-2}, respectively. Furthermore, all data corresponding to a quality flag of 2 were discarded following the two-stage quality procedure presented in Mauder and Foken (2011a). We further discarded latent heat fluxes according to the 97.5% percentile of the H_2O variance and we applied spike removal methods described in Vickers and Mahrt (1997). The amount of data discarded through QC for the respective campaign periods was fairly similar for both set-ups at the sites and is shown in Table 1 of the current document. We consider including Table 1 in the manuscript.

Site	**EC**	**EC-LC**
D AF	8.7%	13.9%
D MC	6.6%	6.8%
F AF	7.1%	6.5%
R AF	11.1%	10.3%
W AF	14.4%	14.6%

Table 1: Amount of data discarded through QC for both set-ups and all sites, e.g. Dornburg AF, “D AF”, Dornburg MC, “D MC”, Forst AF, “F AF”, Reiffenhausen AF, “R AF” and Wendhausen AF, “W AF”.

12. RC: *-Page 8: It would be useful to know the time response of the temperature sensor. Figure B1 does not give a good insight into this response as it convolves: sensor response; sensor noise; housing attenuation and variability of scalar (i.e. RH or T). A look at the spectra/cospectra of the sensors (and a modelled attenuation of the sonic-T would give a much clearer idea (and quantification) of the total combined attenuation of the sensor and housing.*

12. AR: The time response of the temperature sensor was not explicitly stated in the sensor specifications. We think that information on the response time of the derived water vapour mole fraction is of major interest compared to the specific response times of each sensor, e.g. temperature, relative humidity and air pressure. Indeed, Figure B1 is not ideal to present the sensor response, but it gives an idea of how the sensor behaves over a longer time period. And from the figure it is evident that the temperature reading is strongly attenuated and high-frequency fluctuations are filtered.

Nevertheless, we estimated the sensor time constant of the temperature and relative humidity sensor of the BME280 in a lab experiment. The time constant of the temperature sensor was 23.3 ± 0.9 s as a mean over 4 replications. Preliminary results showed a faster time response of the relative humidity sensor. The lab experiment will be continued in the next days and results will be included in the revised manuscript, perhaps in the Materials and Methods section.

13. RC: *-page 9: provide details here, or later on about the timelag. Are you sure this is due to the vertical separation? (if so it should be dependent on W). Alternatively it could be due to the sensor response/processing time and therefore it reasonable to expect it may include a T/RH dependency.*

13. AR: Indeed, the time lag of the low-cost system has different overlapping causes, which include the vertical sensor separation, the mentioned limited response time and the processing time, as well as a dependency on environmental factors, such as relative humidity. We are not able to separate the causes of the time lag and we decided to shorten the sentence mentioned. We will give further information about the time lag of both set-ups later.

14. RC: *-page 15: Fig6 It is interesting to see that the LI-7200 is highly attenuated and more sensitive to RH than the LC system. Indeed attenuation of the LI-7200 in panel c (and even more so in d) is significant and indicates a very poor frequency response for this system. Any thoughts on why? Did you run with filters and did they clog frequently?*

14. AR: Indeed, the frequency response is fairly poor in particular at those plots mentioned. Yes, we used filter for the EC set-up (2 µm), but exchanged those before installing the system in the field, approximately after four weeks.

One reason for the poor frequency response might be a thicker inner intake tube diameter in 2017 (inner diameter of 8.3 mm) relative to 2016 (inner diameter of 5.3 mm) as also discussed in Section 3.4.1. We kept the flow rate of 15 slpm equal in both years. The thinner tube had a Reynolds number of 3950.6 (towards turbulent flow) and the thicker tube had a Reynolds number of 2551.71 (towards laminar flow).

15. RC: *Fig 6, can you please clarify (as I assume that the RH is specific for the LI-7200 and the LC sensor (with its higher temperatures and presumably lower RH). Either way the comparison is complicated: if ambient RH is used, then the sensors are effectively seeing different RH, alternatively if sensor RH is used, then the spectra contain different data (i.e. wind speed/stability might differ). Neither point are likely to be particularly significant to the overall interpretation, but should be clarified.*

15. AR: Along with the raw data of high frequency, we provided 10 second biomet data, such as air temperature, relative humidity, global radiation and air pressure. If biomet data are available EddyPro use those for different flux corrections. Thus, in Fig. 6 the relative humidity classes are derived from ambient relative humidity. Sure, we agree that in this case the comparison of the two different instrumental set-ups is complicated. Nevertheless, the main purpose of this Figure was to show the spectral response characteristics in dependence on different relative humidities separately for each set-up. It was not mend to be a comparison of both set-ups at one particular relative humidity class, because the comparability is not given, as you stated. We clarified this in the manuscript.

16. RC: *Fig 6/7: please include the criteria for data shown, what correlation strength/LE/stability classes are included?*

16. AR: We included information on the filter criteria in the figure captions of Figures 6 and 7, respectively.

17. RC: *-Page 17: The linear regressions are very important and it would be very useful to see the scatter plots associated with these to see if they are well behaved.*

17. AR: The linear regressions between latent heat fluxes obtained by the low-cost EC set-up and the conventional EC set-up were included in Figure 9**.** We showed the scatter plots for all sites and both high-frequency spectral correction methods, e.g. Ibrom et. al. (2007) and Moncrieff et al. (1997), applied to latent heat fluxes obtained by the low-cost EC set-up. We included the linear regression equation, the coefficient of determination and the number of points used for the analysis.

18. RC: *-page 21: figure 12. It is not clear how the 2016 annual ET fluxes were arrived at given the campaign basis of the measurements. Table A3 implies some sites were not measured in 2016.*

18. AR: The data shown in this figure are independent of the campaigns. We conducted continuous measurements of evapotranspiration throughout the year 2016 at the other sites as well, independently if campaigns took place or not. The data shown here are quality checked for implausible values and are not gap-filled. We clarified this also in the manuscript.